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Studies on Earthworm Castings as Substrate for Flowering Pot Plant Production

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Abstract

Experiments were conducted to evaluate earthworm castings (vermicompost) as a substrate for poinsettia (*Euphorbia pulcherrima* Willd.) 'Freedom Red' production. Vermicomposts produced from sheep, cattle, or horse manures were mixed at different ratios with 70:30 peat moss:perlite (PP) (v/v) to create 13 substrates. Chemical and physical properties were measured on all substrates used. Growth index, foliar and bract area, and dry weight were greater on plants grown in substrates with castings from sheep or cattle manure. These castings had greater initial nutrient content than the castings from horse manure. Mixtures of castings and peat produced better plant responses than castings alone. Better plant responses were sometimes associated with values outside the recommended pH and electrical conductivity (EC) levels for poinsettia production. The highest values obtained for growth index, foliar and bract area, dry weight, and root development were produced in the substrates with moderate pore space or water-holding capacity. Substrates with greater pore space produced plants with greater dry weight and root development than substrates with less air space. The highest quality plants were grown in substrates with 25% castings from sheep or cattle manures. In a second experiment, earthworm castings (vermicompost) were evaluated as a substrate amendment for chrysanthemum [*Dendranthema xgrandiflora* (Ramal.) Kitam.] 'Miramar' production. Vermicompost produced from sheep, cattle, and horse manures were mixed at different ratios with 70:30 PP (v/v) to create 12 substrates. The 70:30 PP mix at 100% and Sunshine* Mix 1 were used as control substrates. The bulk density, percentage of pore space, and water-holding capacity increased as vermicompost content increased, while the percentage of air space decreased. Water-holding capacity and bulk density were greatest in 100% vermicompost from sheep manure. Plants grown in mixtures of 50% vermicompost from sheep had a greater growth index at harvest, foliar area, number of flowers per pot, and dry weight, and they required fewer days for flower development than plants grown in other substrates. Vermicompost from sheep manure added at 50% by volume was most effective as a substrate amendment for chrysanthemum production. In a third experiment, the effects of various substrates with or without earthworm [*Eisenia fetida* (Savigny, 1826)] castings on growth of marigolds were evaluated. In addition, the physical and chemical properties of such substrates were determined. Castings had a greater nutrient content than the remaining substrates. The 4:1 pine bark:sand treatment (v/v) (PBS) had higher P, K, and Zn than 7:3 PP (v/v). PP had the lowest nutrient content of all substrates. Castings (C) had the highest pH, followed by 1 PBS: 1 C (v/v), 2 PBS: 1 C (v/v), and 3 PBS: 1 C (v/v). Sunshine Mix 1 and PP had the lowest pH. EC was increased by castings, which had high ER. Castings and PP had the greatest percentage pore space. Water-holding capacity was greatest for 2 PBS: 1 C (v/v) compared with Sunshine Mix 1, followed by castings. Earthworm castings increased plant growth index, stem diameter, root growth, dry weight, and flower number of marigolds, compared with PP, Sunshine Mix 1, and PBS. All mixtures of castings (C) with PP, PBS, except 3 PBS: 1 C (v/v), increased the growth index of plants. 1 PP: 1 C (v/v) increased flower number compared with all substrates without castings. Castings alone increased number of open flowers but did not differ from 1 PP: 1 C or 3 PP: 1 C.

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Introduction

Poinsettia (*Euphorbia pulcherrima* Willd.) is the top-selling potted plant in the United States. An important factor for container production is the container substrate in which the plants are grown because a healthy plant depends on the development of a functional root system (Bilderback, 1982). Artificial, or soilless, substrates are used extensively in the production of containerized greenhouse and nursery crops, including poinsettias (Konduru and Evans, 1999). The selection of an effective growth substrate is important to produce a quality poinsettia (Barnes et al., 1994). When growing poinsettias, the most important features of the growth substrate are that it must be clean and reproducible, and it must have appropriate physical properties for root development (Hartley, 1992). Independent of the origin, the substrate should have a moderate nutrient content and should be porous, well-drained, light in weight, and easy to manage (Tayama and Roll, 1990). Peat moss is the most desirable form of organic matter to include in a poinsettia growth substrate (Barnes et al., 1994; Tomati et al., 1993), but it is becoming increasingly expensive or unavailable (Garrison, 1995; Sanderson and Martin, 1974).

Chrysanthemums are second only to poinsettias in crop value (Miller, 2000). Chrysanthemums are largely leafy plants and naturally heavy feeders during their growing cycle. Most producers grow mums in soilless mixes, which include peat, perlite, and vermiculite (Wang and Pokorny, 1989). As with poinsettias, sphagnum peat moss has been the dominant bulk material in substrates for more than 30 years (Hansen et al., 1993). Since the beginning of the 1990s, environmentalists have been pressing the horticulture industry to avoid heavy use of peat as a growing substrate, claiming that unique, lowland wetlands are being destroyed by the peat extraction procedure (Neal. 1991). As a result, greenhouses are looking for alternatives to the substrates currently used — mixtures of peat, pine bark, vermiculite, and perlite.

New substrate components may offer better conditions for plant growth and at the same time reduce plant production costs when compared with peat moss (Stamps and Evans, 1999). Much research has concentrated on the use of municipal or agricultural wastes for horticultural production. These materials have the disadvantage of composition variability, limited or inconsistent availability, and contamination with undesirable components such as glass, metal fragments, lead, and mercury that make them difficult to work with (Konduru and Evans, 1999). Among these organic materials, livestock manure has been used on agricultural land for centuries and is considered to contain an adequate amount of available phosphorus (Wen et al., 1997). Among all organic wastes, earthworms have shown a preference for animal manures (Laird and Kroger, 1981). Vermicompost production can be profitable and at the same time decrease the environmental impact of animal wastes (Edwards and Fletcher, 1988). Edwards (1988) reported that *Eisenia fetida* is the most common species used on organic wastes for vermicomposting (processing of organic waste with earthworms). Digestion of organic wastes by earthworms with the consequent production of vermicompost can generate an alternative substrate for horticultural industries (Grapelli et al., 1985). The use of vermicompost in horticulture is based on growth improvement for plants when compared with the regular substrates used, compatibility with current technology, and low cost of production (Tomati et al., 1993).

Earthworm compost has potential for horticultural use, particularly as a potted-plant substrate (Buchanan et al., 1988). Tomar et al. (1998) grew *Daucus carota* L. in pots containing soil alone or amended with farmyard manure or vermicompost, and he obtained the greatest yield when vermicompost was used. Kalembasa et al. (1998) evaluated the effect of different sources of N (farmyard manure, ammonium nitrate, and vermicompost produced from waste-activated sludge and from meat processing factory waste) and noted that *Raphanus sativus* L. (Radicula Group) and *Capsicum annuum* L. var. *annuum* (Grossum Group) cultivated in pots produced greater yields when vermicompost was present. Ammonium nitrate also increased *C. annuum* yields, but it decreased *R. sativus* yields.

It has been established that earthworms are one of the most useful and active agents in introducing suitable chemical, physical, and microbiologic changes in the soil. New Zealand did not have native earthworms, and when European species were introduced, grass production doubled (Logsdon, 1994). Growth improvement of specific plants, compatibility with technology, and low cost of production were among the reasons given to support the use of earthworm castings (vermicompost) as a growth medium (Grappelli et al., 1985).

Kang and Ojo (1996) found that higher rice shoot dry weight, lower fertilizer response, and higher nutrient uptake were obtained when rice plants were grown in earthworm castings compared with surface soils. According to Lee (1985), N-containing products of earthworm metabolism are returned to the soil in casts, urine, mucoproteins, and dead earthworm tissue. Growth of annatto (*Bixa orellana*) in plastic bags containing soil inoculated with earthworms was superior to plants grown without earthworms (Pashanasi et al., 1992).

Earthworms influence soil structure by forming macropores, which allow oxygen to enter the soil, whereas micropores between the aggregates give good water-holding capacity (Lavelle, 1988; Willems et al., 1996) In addition to forming macropores and increasing water infiltration, earthworms have been shown to increase soil aggregate stability (Li and Ghodrati, 1995) and water-holding capacity (Stockdill, 1982).

The objectives of this study were to evaluate the suitability of using earthworm castings (vermicompost) as an amendment in substrates used to grow potted marigold, poinsettia, and chrysanthemums and to determine the physical and chemical properties of such substrates.

Materials and Methods

Experiment 1

Castings produced using the red or tiger earthworm, *Eisenia Jetida*, feeding on sheep, cattle, or horse manures were used to create the different substrates evaluated in this experiment. Horse and 75% of the cattle manure (by volume) were harvested from fields of grazing animals feeding on grass and were vermicomposted without any pretreatment. Sheep and 25% of the cattle manure, collected from stables from animals feeding on concentrated feed supplements and hay, were leached with water twice, left for 4 days, and leached again three times to reduce the amount of salt and ammonia present in these manures. Edwards (1988) pointed out that earthworms are very sensitive to ammonia and will not survive in organic wastes containing high amounts of it. Edwards also reported that earthworms will die when high amounts of inorganic salts are present in the waste, but both excessive ammonia and salts can be washed out of the waste. Before leaching, cattle and horse manures used in this experiment had an average electrical conductivity (EC) of 1.25 and 0.90 dS/m respectively, while sheep manure readings were around 13 dS/m.

Five liters of manure and 170 g of mostly adult earthworms (approximately 425 specimens) were placed in a 6.9-L plastic container. The containers were placed in shade to ensure favorable temperature and light for earthworm growth (Edwards, 1988). Each manure was replicated 16 times for a total of 48 plastic containers used in the production of castings. About 1 month was needed for the worms to consume the manure and produce the castings. After 1 month, the worms were removed and the 16 replications of each casting were combined, air-dried, and passed through a 6-mm sieve through which approximately 90% of the castings passed. Twelve substrate treatments were obtained by mixing 70:30 peat moss: perlite (PP) (v/v) and casting from each of the three animal manures at 0:1, 1:3, 1:1, or 3:1 ratios. No lime or other amendments were added to any of the substrate treatments. A 13th treatment, 100% PP with no lime or fertilizer amendments was used as the control. Initial bulk density, percent pore space, percent air space, water-holding capacity, electrical conductivity (EC), and pH of the different substrates were determined using three samples of each treatment substrate. EC and pH were analyzed using a 1:2 dilution. Single samples of the castings and control substrate were delivered to the Mississippi State University Soil Testing Laboratory (Mississippi State, Mississippi) to determine macro- and micronutrient content (Cox, 2001).

Single-rooted cuttings of ‘Freedom Red’ poinsettia (Paul Ecke Poinsettias, Encinitas, California) were transplanted to l-L (15-cm diameter) plastic pots on Sept. 4, 1998, and grown in a polyethylene-covered greenhouse. A night interruption of continuous light from 22:00 to 02:00 HR was used until the start of short days on Oct. 7. The plants were irrigated as needed. The plants were pinched on Sept. 17 to leave six leaves. All plants in the experiment were fertilized using Peter’s 15N-2.15P-20.75K Poinsettia Peat-lite Special (The Scotts Co., Marysville, Ohio) at 200 mg/L N by fertigation any time water was needed, but only tap water was applied during weekends. A tank mix of B-Nine (2,500 mg/L) (Uniroyal Chemical Co., Middlebury, Connecticut) and Cycocel (1,500 mg/L) (Olympic Horticultural Products, Mainland, Pennsylvania) was applied on Oct. 13 for height control. Every 2 weeks, leachate samples were collected from each plant 1 hour after irrigation using the Virginia Tech pour-through technique (Wright, 1986). Leachate pH and EC were measured by using an Accumet Basic pH Meter (Fisher Scientific, Springfield, New Jersey) and a YSI model 35 Conductance Meter (Yellow Springs Instruments, Yellow Springs, Ohio), respectively. At each date of leachate collection, height (h) was measured for each plant from the substrate surface to the shoot apex of the tallest branch. Width (w1) was measured across the side that appeared to be widest, the plant was turned 90°, and a second measurement (w2) was taken. Using these measurements, the growth index was calculated as:

$$\text{Growth Index} = \pi \cdot \{[(w1 + w2)/2]/2\}^2 \cdot h$$

(i.e., a volume estimate).

At anthesis, leaf and bract surface area, root development, depth of substrate, and plant dry weight were determined. Anthesis was determined as pollen shed in at least two of the inflorescences. Total foliar and bract areas were determined using a LI-COR portable area meter (model LI-3000, LI-COR, Lincoln, Nebraska). Root development was scored using a visual scale from 1–5: 1 = roots covering less than 20% of substrate (area in contact with the pot); 2 = roots covering 20–40% of substrate; 3 = roots covering 40–60% of substrate; 4 = roots covering 60–80% of substrate; and 5 = roots covering more than 80% of substrate. Depth of substrate was calculated by measuring from the bottom of the pot to the surface of the substrate. Plant dry weight was measured by drying the leaves, bracts, and stems of each plant at 60°C and then weighing the plant. The experiment was arranged in a completely randomized design using 13 treatments and eight replications (eight plants per treatment). Data were analyzed using PROC GLM (SAS Statistical software, SAS Institute, Cary, North Carolina). Treatment means were separated by Student Newman Keuls’ at 5% significance level.

Experiment 2

Castings produced using the red or tiger worm, *Eisenia fetida* Sav., feeding on *Ovine aries* L. (sheep), *Bas taurus* L. (cattle), or *Equus caballus* L. (horse) manure were used to create the different substrates evaluated in this experiment. Horse and 75% of the cattle manure were collected from grazing animals feeding on grass and were vermicomposted without any pretreatment. Sheep and 25% of the cattle manure, collected from stabled animals feeding on concentrated feed supplements and hay, were leached with water twice, left for 4 days, and leached three more times to reduce the amount of salt and ammonia present (Edwards, 1988). While cattle and horse manures used in this experiment had an average of 1.25 and 0.90 dS/m electrical conductivity (EC), respectively, sheep manure had 13 dS/m EC before leaching.

Five liters of manure and 170 g of mostly adult earthworms (approximately 425 individuals) were placed in each 6,897-cm^3 plastic container. The containers were placed in 60% shade to ensure optimum temperature and light for earthworm survival and growth (Edwards, 1988). Each different manure was replicated 16 times for a total of 48 plastic containers used in the production of castings. *Eisenia fetida* are reported to consume their body weight in organic wastes on a daily basis (Riggle and Holmes, 1994); the earthworms were separated from the castings after 1 month. To remain consistent in treatment, castings from horse, cattle, and sheep manure were separated from the worms after the same length of time. Due to differences in digestion between horse, cattle, and sheep, more undigested cellulose was present in the horse manure that was fed to the worms.

The 16 replications of each casting were combined, then air-dried and passed through a 6-mm sieve to harvest approximately 90% of the castings. Castings were pooled per type of manure. Twelve treatment substrates were obtained by mixing 70:30 peat moss: perlite (PP) (v/v) with castings from each of the three animal manures at 100%, 75%, 50%, or 25%. PP with no added castings and Sunshine* Mix 1 (SunGro Horticulture, Bellevue, Washington) represented treatments 13 and 14, respectively, and were used as controls.

Four rooted cuttings of *Dendranthema xgrandiflora* 'Miramar' (Yoder Bros., Barberton, Ohio) were transplanted per l-L (15-cm diameter) plastic pot on Feb. 19, 1999, and grown in a double-layer polyethylene-covered greenhouse. Night interruption lighting from 2200 to 0200 HR was used until March 4. The plants were irrigated as needed. The plants were pinched on March 3, removing approximately 2.5 cm of new growth. All plants in the experiment were fertilized using Peter's 15N-4.3P-24.9K Pot Mum Special (The Scotts Co., Marysville, Ohio) at 300 mg/L N by fertigation, except weekends when clear water was applied. Plants were covered with black cloth from 17:00 to 08:00 HR starting on March 26 until flower color development on April 11. Bulk density, percent pore space, percent air space, water-holding capacity, EC, and pH of the substrates were determined on three samples of each treatment substrate at the beginning of the experiment. Single samples of 100% castings and the control substrates were delivered to the Mississippi State University Soil Testing Laboratory (Mississippi State, Mississippi) to determine macro- and micronutrient content (Cox, 2001). Every 2 weeks, leachate samples were collected from each pot 1 hour after irrigation using the Virginia Tech pour-through technique (Wright, 1986; Wright et al., 1990). Leachate pH and EC were measured using an Accumet Basic pH Meter (Fisher Scientific, Springfield, New Jersey) and a YSI model 35 Conductance Meter (Yellow Springs Instruments, Yellow Springs, Ohio), respectively. At 4 and 10 weeks after planting (2 and 8 weeks after pinching), height (h) was measured for each pot from the substrate surface to the shoot apex of the tallest branch. Canopy width (w1) was measured across the side that appeared to be widest, the plant was turned 90°, and a second canopy width measurement (w2) was taken. Using these measurements, the growth index was calculated as:

$$\text{Growth Index} = \pi \cdot \{[(w1 + w2)/2]/2\}^2 \cdot h$$
(i.e., a volume estimate).

At harvest, leaf area, days to harvest, flower number, substrate depth, and shoot dry weight were determined. Plants were harvested when at least five flowers in the pot showed petals at least 3 mm long. Total foliar area was determined using a portable area meter (model LI-3000, LI-COR, Lincoln, Nebraska). Substrate depth was measured from the bottom of the pot to the surface of the substrate. Shoot dry weight was measured per pot on all aboveground growth dried at 60°C.

The experiment was arranged in a completely randomized design using 14 treatments and eight single-pot replications. Data were analyzed using contrast procedures to determine differences between vermicompost concentrations within compost type. Comparisons between types of compost at each concentration were separated using Fischer's protected least significant difference (LSD) means separation test with P=0.05 (Statistical Analysis Software, SAS Institute, Gary, North Carolina).

Experiment 3

This research was conducted at the Mississippi State University horticulture greenhouses. African Marigold 'Marvel Orange' (*Tagetes erecta*) were seeded (two seeds per hole) into 1,030 plastic flats using Sunshine Mix 1 (75% Canadian spaghum moss, 25% perlite, nutrients with gypsum, dolomitic lime, and a wetting agent) as germination substrate. Flats were watered and covered with a transparent plastic cover, and placed on a bench with artificial light. Seedlings were relocated to the greenhouse when they had four true leaves. Then, 100 mg/L N of 20-4.4-16.6 N-P-K fertilizer was applied to the seedlings to promote growth and prepare seedlings for transplanting. Plants of uniform size were chosen from the flats and transplanted into 10x10-cm square plastic pots filled with the substrates to be tested. After transplanting, plants were placed on a greenhouse bench in a completely randomized design and irrigated daily. No additional fertilizer was applied to the plants to compare the effect of substrates on plant growth without the effect of external fertilizer application. Substrates evaluated were Sunshine Mix 1, 70:30 peat: perlite (v/v) (PP), 4:1 pine bark: sand (v/v) (PBS), and earthworm castings (C) sieved to 6 mm. In addition, mixtures of PP and

PBS with castings C at 1:1, 2:1, and 3:1 (v/v) ratios were evaluated for a total of 10 treatments. Castings were produced using cow manure as the only food source for the earthworms. Vermicomposting methodology involved harvesting cow manure from fields of grazing animals feeding on grass. Five liters of manure and 170 g of mostly adult earthworms (approximately 425 specimens) were place in 6.9-L plastic containers. Containers were placed in the shade to ensure favorable temperature and light for earthworm growth (Hidalgo and Harkess, 2002a). Sixteen containers were used in the production of castings. After 30 days, the worms were removed, and castings were air-dried and passed through a 6-mm sieve. Substrates with PP and PBS were buffered using 4.5 kg/m^3 of calcium carbonate provided by dolomitic limestone (52% $CaCO_3$).

Data including stem height and diameter were collected weekly. The plant growth index was calculated using the formula $GI = \pi \cdot r^2 \cdot h$, where GI = growth index, π = 3.145, r = ratio of foliage, and h = stem height. Other parameters evaluated were number of flowers per plants, number of opened flowers per plants, and root growth on a 1–5 scale (1 = poor growth, 5 = excellent growth). In addition, plant dry weight (roots not included) was determined by drying plant parts in an oven at 60°C for 48 hours. Bulk density, percent pore space, percentage air space, water-holding capacity, electric conductivity (EC), and pH of the treatment substrates were determined using three samples of each substrate (Hidalgo and Harkess, 2002a, 2002b). EC and pH were analyzed using a 1:2 dilution. Samples of the treatment substrates were delivered to the Mississippi State University Soil Testing Laboratory (Mississippi State, Mississippi) to determine nutrient content using the Lancaster Soil Test Method (Cox, 2001).

The experimental design was a completely randomized design with 10 treatments and 10 replications (10 plants per treatment). Data were analyzed by analysis of variance using SAS (SAS Institute, Cary, North Carolina). Treatment means were separated using Duncan's multiple range test, 5% probability.

Results and Discussion

Experiment 1

Substrates consisting of 0 PP: 1 castings (C) had greater macro- and micronutrient content than the control (Table 1). The amount of each nutrient was proportionally reduced as the amount of peat moss increased in the mixture for the three different castings evaluated (data not shown). All the casting substrates had greater nutrient content than the peat perlite control.

Within casting type, bulk density was greatest at 0 PP: 1C and decreased as the peat content increased (Table 2). Bulk density was greatest in the 0 PP: 1 SC (sheep casting) and 0 PP: 1 HC (horse casting) substrates, followed by 1 PP: 3 SC. All substrates with castings had a greater bulk density than the control (1 PP: 0 C). Among castings, HC at 1 PP: 1 HC had the most pore space. Mixing HC with peat reduced total pore space, but total pore space was similar at 1 PP: 3 HC and 1 PP: 1 HC. Mixtures of 1 PP: 3 HC were similar in total pore space to those of 0 PP: 1 CC (cattle castings) and 1 PP: 3 CC. The control (1 PP: 0 C) had the least total pore space of all other substrates used. The greatest percent air space was in the control substrate, but it was similar to mixtures of peat and any castings at 3 PP: 1 C

Table 1. Nutrient content of earthworm casting and 70:30 peat: perlite (v/v) used to grow Poinsettia 'Freedom Red' plants.[1]

Substrates	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu
	mg/g	*mg/g*	*mg/g*	*mg/g*	*mg/g*	*µg/g*	*µg/g*	*µg/g*	*µg/g*	*µg/g*
0 PP : 1SC[2]	35.2	13.7	12.7	30.2	7.2	1,000	1,711	314	215	10
0 PP : 1 CC[3]	45.4	14.3	7.4	61.6	11.1	1,500	1,285	380	204	40
0 PP : 1HC[4]	39.1	9.5	8.3	18.5	5.6	860	1,672	245	204	12
1 PP : 0 C[5]	14.3	0.1	0.1	2.5	0.9	0[6]	668	22	78	2

[1]Single samples were used for each analysis.
[2]Peat moss/perlite : casting from sheep manure.
[3]Peat moss/perlite : casting from cattle manure.
[4]Peat moss/perlite : casting from horse manure.
[5]Peat moss/perlite : casting (control).
[6]Content too low to accurately measure

Table 2. Physical properties of the substrates used to grow poinsettia 'Freedom Red.'

Substrates	Bulk density	Total pore space	Air space	WHC[1]
	kg/L	%	%	%
0 PP : 1 SC[3]	0.24a[2]	80.19b	10.33de	69.85b
1 PP : 3 SC	0.20b	75.07d	9.73e	65.33d
1 PP : 1 SC	0.16d	72.49e	10.24de	62.26f
3 PP : 1 SC	0.12f	71.49e	12.80ab	58.70h
0 PP : 1 CC[4]	0.16d	78.97bc	8.23f	70.74b
1 PP : 3 CC	0.15e	78.27c	10.47de	67.80c
1 PP : 1 CC	0.12f	75.63d	11.90abc	63.73e
3 PP : 1 CC	0.10g	70.93e	12.33abc	58.59h
0 PP : 1 HC[5]	0.24ay	83.07a	10.03de	73.04a
1 PP : 3 HC	0.19c	79.08bc	11.20cd	67.88c
1 PP : 1 HC	0.16d	78.10c	12.20abc	65.90d
3 PP : 1 HC	0.12f	72.11e	11.74bc	60.37g
1 PP : 0 C[6]	0.08h	67.59f	13.08a	54.51i

[1]Water-holding capacity.
[2]Means in columns separated by Student-Newman-Keuls' at 5% significance level. Means in columns followed by the same letter do not differ.
[3]Peat moss/perlite: casting from sheep manure.
[4]Peat moss/perlite: casting from cattle manure.
[5]Peat moss/perlite: casting from horse manure.
[6]Peat moss/perlite: casting (control).

or 1 PP: 1 CC. Water-holding capacity, similar to bulk density, increased as the amount of castings increased. The greatest values for water-holding capacity occurred when substrates consisted of 100% castings (0 PP: 1C). All the mixtures of PP: C had greater water-holding capacity than the control.

From 2 weeks after planting until anthesis, leachate pH from SC and HC substrates decreased as casting content decreased (Table 3). This trend was similar for CC substrates up to 8 weeks after planting, when the pH among substrates with 100% or 75% castings was similar. This remained true until harvest. At all sample times, substrates with castings had a higher pH than the control. Castings obtained in our experiment had a high pH value similar to that of the original manures. Manures from sheep, cattle, and horses had average pH equal to 7.9, 7.6, and 7.7, respectively. The control substrate had very low leachate pH readings because it had no added lime amendments. Lime is normally included as an amendment in greenhouse substrates.

In all substrates containing castings, EC was greater than in the control leachate at all sample dates except weeks 10 and 12, when EC levels for leachates from the control and 3 PP: 1 CC were similar (Table 4). From weeks 8 to 12 after transplant, EC of the leachate from the substrates formulated from SC and CC

Table 3. Leachate pH of earthworm castings and peat/perlite substrates during growth of 'Freedom Red' poinsettia.

Substrates	Leachate — Weeks after transplant					
	2	4	6	8	10	12
0 PP : 1 SC[2]	7.82b[1]	7.64a	7.60a	7.46a	7.30bc	7.24b
1 PP : 3 SC	7.26b	7.26b	7.12c	7.16b	7.03de	7.08cd
1 PP : 1 SC	6.07g	6.27e	6.49e	6.70d	6.76fg	6.70e
3 PP : 1 SC	5.13i	5.31g	5.72g	6.04f	6.44h	6.19f
0 PP : 1 CC[3]	8.00a	7.75a	7.57a	7.62a	7.57a	7.61a
1 PP : 3 CC	7.46c	7.36b	7.35b	7.51a	7.52ab	7.60a
1 PP : 1 CC	6.50f	6.56d	6.83d	7.08b	7.17cd	7.20bc
3 PP : 1 CC	5.16i	5.28g	5.64g	5.86g	6.34h	6.16f
0 PP : 1 HC[4]	7.31d	7.27b	7.23bc	7.18b	7.10cde	7.17bc
1 PP : 3 HC	6.62e	6.70c	6.86d	6.86c	6.91ef	6.98d
1 PP : 1 HC	5.69h	5.89f	6.15f	6.35e	6.55gh	6.63e
3 PP : 1 HC	4.69j	4.70h	5.10h	5.14h	5.39i	5.38g
1 PP : 0 C[5]	3.85k	4.26i	4.37i	4.44i	4.92j	4.69h

[1]Means in columns separated by Student-Newman-Keuls' 5% significance level. Means in columns followed by the same letter do not differ.
[2]Peat moss/perlite: casting from sheep manure.
[3]Peat moss/perlite: casting from cattle manure.
[4]Peat moss/perlite: casting from horse manure.
[5]Peat moss/perlite: casting (control).

Substrates	Weeks after transplant 2	4	6	8	10	12
	dS/m	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*
0 PP : 1 SC[2]	3.44a[1]	1.83bcd	1.50b	1.07ab	0.93a	0.81a
1 PP : 3 SC	3.24a	1.83bcd	1.47bc	1.02abc	0.75b	0.65bc
1 PP : 1 SC	2.63bc	2.12b	1.29bcd	0.83d	0.52d	0.48de
3 PP : 1 SC	3.32a	1.71cd	0.61e	0.39e	0.27ef	0.24f
0 PP : 1 CC[3]	3.26a	2.60a	1.78a	1.18a	0.71bc	0.57cd
1 PP : 3 CC	3.03ab	1.96b	1.48b	0.83cd	0.52d	0.43e
1 PP : 1 CC	3.23a	2.69a	1.42bc	0.77d	0.56d	0.47de
3 PP : 1 CC	3.23a	1.70cd	0.65e	0.45e	0.23fg	0.21fg
0 PP : 1 HC[4]	2.62bc	1.53de	1.16d	0.87cd	0.61cd	0.49de
1 PP : 3 HC	2.32c	2.12b	1.29bcd	1.11ab	0.82ab	0.70b
1 PP : 1 HC	2.22c	1.81bcd	1.24cd	0.96bcd	0.61cd	0.49de
3 PP : 1 HC	1.46d	1.27e	0.65e	0.53e	0.38e	0.25f
1 PP : 0 C[5]	0.64e	0.25f	0.25f	0.23f	0.14g	0.12g

Table 4. Leachate electrical conductivity of earthworm casting and peat/perlite substrates during growth of 'Freedom Red' poinsettia plants.

[1]Means in columns separated by Student-Newman-Keuls' at 5% significance level. Means in columns followed by same letter do not differ.
[2]Peat moss/perlite : casting from sheep manure.
[3]Peat moss/perlite : casting from cattle manure.
[4]Peat moss/perlite : casting from horse manure.
[5]Peat moss/perlite : casting (control).

decreased as the amount of castings decreased in the substrate. In the leachate from the 1 PP: 3 HC substrate, EC levels were greater than in the substrate with 0 PP: 1 HC at 4, 8, 10, and 12 weeks after planting.

Within casting substrate type, poinsettia growth index was greatest for plants in substrate 3 PP: 1 C and least for plants in substrates 0 PP: 1 C at 2 weeks after pinching (Table 5). In SC and CC substrates, at 10 weeks after pinching, plants in 1 PP: 3 C were larger than the plants in 0 PP: 1 C or 3 PP: 1 C substrates. Within HC substrates, 0 PP: 1 HC yielded the largest plants at 10 weeks. At 10 weeks after pinching, the controls were significantly smaller than all treatments except SC at 0 PP: 1 SC. The limited growth of the plants in the control substrate was most likely the result of the low pH in absence of lime amendment.

Table 5. Growth and development of 'Freedom Red' poinsettia produced in earthworm casting and peat/perlite substrates.

Substrates	Growth index[1] weeks after pinching 2	10	Foliar area	Bract area	Dry weight	Root development[2]
	cm³	*cm³*	*cm²*	*cm²*	*g*	
0 PP : 1 SC[4]	2,50f[3]	14,598hi	1,137.9f	1,674.7e	11.68g	2.0g
1 PP : 3 SC	877e	33,048bc	1,855.3bc	3,478.6ab	20.80cde	2.6ef
1 PP : 1 SC	1,550cd	28,823cd	1,771.1cd	3,201.2b	21.81cd	3.8b
3 PP : 1 SC	2,977a	26,184de	1,788.7bc	2,661.7c	25.39ab	4.8a
0 PP : 1 CC[5]	630ef	33,556b	1,735.0cd	3,363.5ab	19.29def	2.4fg
1 PP : 3 CC	1,566cd	40,419a	2,075.2a	3,711.0a	23.30bc	3.3bcd
1 PP : 1 CC	2,302b	30,422bcd	1,988.9ab	3,264.9b	26.40a	3.6bc
3 PP : 1 CC	2,953a	2,202gefg	1,988.4ab	2,691.2c	26.40a	4.8a
0 PP : 1 HC[6]	226f	29,438bcd	1,337.4ef	2,578.1c	17.09f	3.0de
1 PP : 3 HC	658ef	22,625ef	1,363.ge	2,580.3c	18.29ef	3.1cde
1 PP : 1 HC	991e	17,647gh	1,369.3e	2,150.1d	20.74cde	3.5bcd
3 PP : 1 HC	1,889bc	18,363fgh	1,580.1d	2,387.0cd	20.48cde	4.4a
1 PP : 0 C[7]	1,141de	10,866i	861.0g	1,560.5e	12.53g	4.6a

[1]$GI = \pi \cdot \{[(w1 + w2)/2]/2\}^2 \cdot h$
[2]1 = roots covered <20% of substrate (area in contact with the pot); 2 = roots covering 20–40% of substrate; 3 = roots covering 40–60% of substrate; 4 = roots covering 60–80% of substrate; and 5 = roots covering more that 80% of substrate.
[3]Means in columns separated by Student-Newman-Keuls' at 5% significance level. Means in columns followed by the same letter do not differ.
[4]Peat moss/perlite : casting from sheep manure.
[5]Peat moss/perlite : casting from cattle manure.
[6]Peat moss/perlite : casting from horse manure.
[7]Peat moss/perlite : casting (control).

Table 6. Total elemental content of soilless substrates and vermicomposts from three manure types.										
Substrates	N	P	K	Ca	Mg	S	Fe	Mn	Zn	Cu
	mg/g	*mg/g*	*mg/g*	*mg/g*	*mg/g*	*μg/g*	*μg/g*	*μg/g*	*μg/g*	*μg/g*
Sheep castings	35.2	13.7	12.3	30.2	7.2	1,000	1,711	314	215	10
Callie castings	45.4	14.3	7.4	31.6	11.1	1,500	1,285	380	337	40
Horse castings	39.1	9.5	8.3	18.5	5.6	860	1,672	245	204	12
70 peat : 30 perlite	14.2	0.1	0.1	2.5	0.9	n/d[1]	668	22	78	2
Sunshine Mix 1	16.5	0.7	1.5	25.9	7.7	n/d[1]	774	58	39	7

[1]Not determined.

During the first 4 weeks after pinching, plant growth index decreased as the amount of casting in the mixtures decreased (data not shown). For the last observation, the greatest plant growth index was observed in the 1 PP: 3 CC substrate (Table 5). Growth indices of plants grown in 0 PP: 1 CC, 1PP: 1 CC, 1 PP: 3 SC, and 0 PP: 1 HC were similar at week 10.

Plants in all substrates with castings had greater foliar area than those in the control (Table 5). Plants in all substrates except 0 PP: 1 SC had greater bract area than those in the control substrate. Within SC substrate, plants in 0 PP: 1 SC had the least foliar and bract area, while bract area was greatest for poinsettias in substrates with 1 PP: 3 SC and 1 PP: 1 SC. The addition of peat to the CC resulted in increased poinsettia foliar area (Table 5). However, bract area was least on plants grown in 3 PP: 1 CC. Foliar area was greatest among plants in the HC substrates when mixed at 3 PP: 1 HC. Bract area was less on poinsettias in 1 PP: 1 HC than those in 0 PP: 1 HC or 1 PP: 3 HC. Substrates with 1 PP: 3 CC produced plants with greater foliar area than in any substrate containing SC or HC. Compared with 1 PP: 3 CC, poinsettia bract area was similar among plants in 0 PP: 1 CC and 1 PP: 3 SC (Table 5). These three substrates yielded greater bract area than all the HC substrates. Bract area was greater for plants in 0 PP: 1CC, 1PP: 3 CC, 1 PP: 1CC, 1 PP: 3 SC, and 1 PP: 1 SC than any other substrate (Table 5). Plants in 3 PP: 1 SC and 3 PP: 1 CC substrates had similar bract area to plants grown in 0 PP: 1 HC, 1 PP: 3 HC, and 3 PP: 1 HC. Bract area of plants grown in 1 PP: 1 HC or 3 PP: 1 HC were similar.

Within each casting type, in general, root development was greater when plants were grown in substrates consisting of at least 3 PP: 1 C (Table 5). Within CC substrates, plants in 0 PP: 1 CC had the least root development. Those in HC substrates 1 PP: 1 HC, 1 PP: 3 HC, and 0 PP: 1 HC had reduced root development. The greatest root development was found in substrates that had increased air space and decreased water-holding capacity (Tables 2 and 6). However, these substrates also had lower total pore space. The decrease in root development seen with increased amounts of casting appeared to be correlated to increased bulk density, leachate pH, and EC as casting content increased (Tables 2, 3, and 4). However, better root development seemed unrelated to greater foliar or bract area.

Increased plant dry weight was associated with a greater amount of peat in the mixture, but one of the two lowest plant dry weights was observed in the substrate consisting of 100% PP (Table 5). Plant dry weight in substrates with 0 PP: 1 SC was similar to that in the control substrate and was greatly reduced compared with those of plants in all other formulations. Bulk density of 0 PP: 1 SC was one of the greatest (Table 2). In CC substrates, plants in 0 PP: 1 CC had the lowest dry weight, followed by the plants in 1 PP: 3 CC (Table 5). These substrates also produced plants with the greatest growth index and bract area, whereas 1 PP: 3 CC produced plants with the greatest foliar area. The largest growth index but lowest dry weight observed in these plants could indicate greater cell enlargement without an increase in photosynthate accumulation in those plants grown in such substrates. All plants grown in substrates with HC had dry weights less than those in substrates with 3 PP: 1 SC or 1 PP: 1 CC and 3 PP: 1 CC.

As castings content increased, substrate shrinkage increased (data not shown). The 0 PP: 1 CC substrate shrank more than any other substrate. This pattern of shrinkage was similar to the decrease in root growth also observed with increased casting content (Table 5). While shrinkage was greatest in the HC substrates, within substrate type, a similar trend to increased growth with a decrease in castings was observed. Therefore, growth differences were not likely due to possible changes in physical properties from substrate shrinkage, but were more likely due to the initial physical and chemical properties of the substrates.

Greatest values of growth index, foliar and bract area, and dry weight were obtained in mixtures with castings from sheep and cattle manure. Only bract area — for plants grown in 0 PP: 1 CC — was as good as or better than bract area in plants grown in mixtures of peat and castings (Table 5). Foliar area, bract area, and dry weight of plants grown in mixtures of PP: SC were more than 0 PP: 1 SC. Foliar area and dry weight were higher for CC when mixed with peat than when used alone. Castings from cattle and sheep manures had higher initial values for most of the nutrients evaluated than castings from horse manure (Table 1). Greater initial nutrient concentrations may have provided better conditions for growth. During the earthworm digestion, nutrients bound in the organic form (N, P, S) have been shown to be mineralized and made more available to the plant (Coleman et al. 1983; Richard, 1974). There was a proportional decrease in initial nutrient content due to dilution with the addition of peat. Plants did not grow as large in 100% castings as in substrates where peat was added. Since the initial amount of nutrients in the substrates and the different growth parameters evaluated were apparently unrelated, other substrate characteristics must be considered.

The optimum pH range for nutrient availability in soilless substrates is generally lower than for field soils — approximately 5.0 to 5.5 or 6.5 (Nelson, 1991). Poinsettia grows best in soilless substrates with a pH range between 5.8 and 6.3 (Dole and Wilkins, 1999). Mixtures at the ratios 3 PP: 1 SC, 3 PP: 1 CC, and 1 PP: 1 HC are the only substrates with values in that range (Table 3). The rest of the mixtures tended to have a higher pH, except for a few exceptions where pH values were less than 5.6. In our experiment, the greater plant growth index values were produced in substrates with pH values above those recommended for poinsettia production. Barley (1961) considered that the increased pH of earthworm castings was responsible for a higher solubility of nutrients and thus increased availability.

When plants were grown in mixtures with SC, some of the highest values for foliar area, dry weight, and root development were obtained in the mixtures with the lower electrical conductivity values. For those plants grown in CC mixtures, foliar area, bract area, dry weight, and root development were greater in those mixtures containing peat. Root development on plants grown in HC substrates was also greater in substrates with the lowest EC values. Plants grown in 3 PP: 1 HC produced the greatest root development. These root development results were similar to those obtained with the control substrate, which had the least electrical conductivity of all the substrates tested. Castings have been reported to stimulate root initiation, root elongation, and root biomass of ornamental plants, with the best results obtained when castings alone were used (Grapelli et al., 1985). However, in this study the opposite was observed since root development decreased as the amount of castings increased.

Nelson (1991) reported that an EC level of 2–4 dS/m is suitable for most greenhouse crops, and a lower level — 0.75 or lower — is better for very young plants or rooted cuttings. The best range to grow poinsettia plants of the Freedom family is reported to be between 1.5 and 2 dS/m (Hartley, 1998, personal communication). Substrates with 25% casting had decreased electrical conductivity levels earlier in production, possibly explaining the greater growth index values at harvest.

Air space increased when the amount of casting decreased in the substrate. Dry weight and root development followed the same trend. Bulk density, pore space, and water-holding capacity showed the opposite trend. The greatest plant growth index, foliar bract area, dry weight, and root development failed to coincide with the greatest bulk density, pore space, or water-holding capacity.

Comparing the results obtained with the peat:castings mixtures and the control, in general, all mixtures produced better results than the control. The poor growth of the plants in the control substrate was likely a result of the lower substrate pH. Poinsettias were larger when grown in 25% castings than when grown in a substrate with greater casting content. Castings from sheep and cattle manure yielded higher quality, larger poinsettias than castings from horse manure. High pH values associated with castings in the substrate — even above the pH values recommended for poinsettia production — did not have a detrimental effect on plant growth. The improved growth of plants in substrates with castings compared with the control may be due in part to the higher pH of substrates with castings. The addition of castings at 25% increased growth and bract development, which improved plant quality. Plant growth was significantly affected by the source of organic matter used in vermicompost production. Castings were demonstrated to be a suitable substrate amendment for poinsettia production. Poinsettias produced in substrates with 25% castings from sheep or cattle manures were about twice as tall as the container they were grown in, had dark green foliage, and were of saleable quality.

Experiment 2

Worm castings appeared to have higher macro- and micronutrient content than the controls (Table 6) with the exception of Ca and Mg, where Sunshine* Mix 1 had values greater than the casting from horse manure. The amount of each nutrient was proportionally reduced as the amount of peat moss increased in the mixture for the three different castings evaluated (data not shown).

Within casting type, bulk density increased as the peat content decreased (Table 7). Sheep castings had greater bulk density than cattle or horse castings. Both controls had lower bulk density than the substrates with castings. With increasing castings content, pore space decreased before increasing as casting content approached 100%. Sheep castings had the least pore space compared with the cattle and horse castings. Percentage of air space was greatest when casting content was least for all casting types. At 100% castings, sheep castings had less air space than cattle or horse castings. As casting content increased, water-holding capacity increased. Sheep castings generally had greater water-holding capacity than cattle or horse castings. The commercial substrate control had the least bulk density at 0.08 g/cc with a pore space of 90% and water-holding capacity of 61%. Percentage of air space in the commercial substrate was less than in the peat control. Sheep and cattle are ruminants and more completely digest cellulose than do horses. The large particles of undigested cellulose in the horse manure were difficult for the worms to eat and thus remained in the finished castings, increasing the air space and decreasing water-holding capacity. Sheep in the pasture will feed on shorter, tenderer grasses than cattle. It is likely the more tender grasses would digest more completely. When consumed by earthworms, the resulting castings were denser and had greater bulk density than castings from cattle or horse. Values of total porosity and bulk density for peat moss were similar to those reported by Fonteno (1993).

Within each casting type and at each measurement date, leachate pH increased as the casting content increased (Table 8). Castings are more basic than peat moss, resulting from the basic nature of animal manure. When measured at week 2, 4, 6, 8, or 10, substrates with high castings content remained more basic than the peat moss control. At 100%, castings from horse manure were consistently more acidic than those from cattle or sheep manure. The lower water-holding capacity and greater undigested cellulose content of the castings from horse manure may contribute to the lower pH of the leachate. At 25% castings, there was no difference between the castings from cattle and horse manure. The pH of the Sunshine Mix 1 commercial substrate was similar to the 75% or 100% casting concentrations ranging from 6.1 at week 2 to 6.7 at week 10.

Leachate EC when measured at 2 weeks after planting increased as casting content increased to 50% or 75% before again decreasing in casings from sheep and horse, respectively (Table 9). Leachate EC from cattle castings was greater than the control but increased little as the casting content increased. At 4 weeks, only the castings from sheep increased then decreased in leachate EC as castings concentration increased. The leachate EC from the cattle and horse castings increased linearly with concentration. After 8 weeks, regardless of casting concentration or type, there were no differences in leachate EC. At weeks 2 and 4, castings from sheep had greater leachate EC than cattle or horse at 25% to 100% cast-

Table 7. Physical properties of the treatment substrates composed of vermicompost (worm castings) from sheep, horse, or cattle manure and a 70:30 peat moss : perlite mixture (v/v).[1]

Castings	Bulk density			Pore space			Air space			Water-holding capacity		
%	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse
	g/cc	*g/cc*	*g/cc*	%	%	%	%	%	%	%	%	%
0	0.09a[2]	0.09a	0.09a	86a	86a	86a	36a	36a	36a	51a	51a	51a
25	0.13b	0.12a	0.11a	86b	84a	89b	31b	24a	32b	55a	60b	57a
50	0.25c	0.13a	0.14b	80a	86b	84b	16a	25b	24b	63b	61a	60a
75	0.22c	0.15a	0.17b	85a	87b	85a	19a	19a	26b	66b	68b	59a
100	0.28c	0.16a	0.17b	90a	93b	92b	12a	24b	27b	77c	69b	66a
Significance	L***	L***	L***	L**	L***	L***	L***	L***	L***	L***	L***	L***
	Q***	Q*	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q**	Q***	Q[NS]

[1]BD = 0.08, pore space = 90%, air space =30%, and water-holding capacity = 61% in Sunshine Mix 1 (SunGro Horticulture, Bellevue, Washington), a commercial substrate used as an additional control.
[2]Means separation using least significant differences at P≤0.05 within percentage of castings (n=6). Means in rows followed by the same letter do not differ. NS = Nonsignificant. *, ** , and *** = significant at P ≤ 0.05, 0.01, and 0.001, respectively. L=Linear, Q=Quadratic.

Table 8. Leachate pH measured every 2 weeks after planting until harvest of 'Miramar' chrysanthemum grown in vermicompost substrates.[1]

Castings (%)	Week 2			Week 4			Week 6			Week 8			Week 10		
	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse
0	3.5a[2]	3.5a	3.5a	4.0a	4.0a	4.0a	3.5a	3.5a	3.5a	3.6a	3.6a	3.6a	4.6a	4.6a	4.6a
25	5.3b	4.5a	4.6a	5.8b	5.0a	5.1a	5.3b	4.4a	4.3a	5.4b	4.1a	4.3a	6.2b	5.5a	5.5a
50	5.5a	6Ac	5.8b	5.9a	6.7e	6.2b	5.3b	5.6c	4.8a	5.9b	5.5ab	5.2a	6.6b	6.0a	5.8a
75	7.4b	7.5b	5.9a	7.5b	7.6b	6.1a	7.De	6.4b	5.1a	6.7b	6.4b	4.8a	6.4b	6.2b	5.5a
100	8.0b	8.1b	7.3a	8.0b	7.9b	7.1a	7.4e	6.8b	5.8a	6.9b	6.6b	5.6a	6.7b	6.4b	5.9a
Significance	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***
	Q**	Q***	Q^{NS}	Q***	Q***	Q***	Q***	Q***	Q^{NS}	Q***	Q^{NS}	Q^{NS}	Q***	Q**	Q**

[1]Substrates were composed of vermicompost (worm castings) from sheep, horse, or cattle manure and a 70:30 peat moss: perlite mixture (v/v). Leachate pH was 6.1 at week 2, 7.0 at week 4, 6.1 at week 6, 6.6 at week 8, and 6.7 at week 10 in Sunshine Mix 1 (SunGro Horticulture, Bellevue, Wash), a commercial substrate used as an additional control.
[2]Means separation using least significant differences at $P \leq 0.05$ within percentage of castings (n=8). Means in rows followed by the same letter do not differ. NS = Nonsignificant. *, ** , and *** = significant at $P \leq 0.05$, 0.01, and 0.001, respectively. L=Linear, Q=Quadratic.

ings. At week 6, this trend reversed and castings from sheep had a reduced leachate EC compared with cattle and horse at 50% or greater castings. Leachate EC equalized between substrates over time due to initial high nutrient concentrations either being used by the plants or leached through regular irrigation events. The initial increase in leachate EC and later decrease as castings concentration increased may be due to changes in porosity of the substrates as concentration of peat moss decreased. Total porosity (Table 7) decreased before increasing as casting concentration increased. The leachate EC of the commercial substrate control was similar to the peat moss: perlite control at each week.

At 4 and 10 weeks after planting, the greatest plant growth was observed in substrates containing 50% sheep castings or 25% cattle or horse castings (Table 10). For all casting types, growth increased then decreased as castings concentration increased. When 25% casting was used, there was no difference in growth between casting type 4 weeks after planting. However, at 50% casting, the largest plants were growing in sheep castings. When casting content was 25% or 50%, the plants grew more in sheep castings after 10 weeks than in cattle or horse castings. Kiepas et al. (1998) also reported a negative effect on growth of tomato at 100% castings. At both 4 and 10 weeks after planting, plants in horse castings grew as large as or larger than those in sheep castings at 75% or 100% castings. The greater growth in the horse castings at 75% or 100% castings may be attributed to the decreased water-holding capacity of these substrates. A decrease in water-holding capacity increased the number of irrigations, and thus the amount of fertilizer the plants received, which may account for the greater growth. However, the largest plants overall were those grown in either 50% sheep castings or 25% cattle or horse castings. In addition, the substrate pH was lower in the horse than the cattle and sheep casting substrates at the 75% and 100% concentrations. The largest plants in

Table 9. Leachate electrical conductivity measured every 2 weeks after planting until harvest of 'Miramar' chrysanthemum grown in vermicompost substrates.[1]

Castings (%)	Week 2			Week 4			Week 6			Week 8			Week 10		
	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse
%	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*	*dS/m*
0	0.6a[2]	0.6a	0.6a	0.3a	0.3a	0.3a	1.6a	1.6a	1.6a	1.3a	1.3a	1.3a	1.4a	1.4a	1.4a
25	2.7b	1.2a	1.2a	1.4b	0.4a	0.4a	2.6b	2.1a	2.1a	1.5a	1.4a	1.3a	1.3a	1.6a	1.5a
50	3.5b	1.2a	1.4a	1.5b	0.6a	0.6a	2.4a	2.4a	2.2a	1.1a	1.7b	1.1a	1.0a	1.9b	1.3a
75	2.3c	1.0a	1.5b	1.1b	0.7a	0.8ab	1.0a	2.3b	1.8b	1.4a	1.4a	1.2a	2.2b	1.4a	1.7a
100	1.6b	1.2a	1.1a	0.9ab	0.7a	1.0b	1.2a	1.9b	1.8b	1.1a	1.3a	1.1a	1.4a	1.5a	1.0a
Significance	L***	L**	L***	L**	L**	L***	L***	L^{NS}	L^{NS}	L^{NS}	L^{NS}	L^{NS}	L^{NS}	L^{NS}	L^{NS}
	Q***	Q*	Q***	Q***	Q^{NS}	Q^{NS}	Q***	Q**	Q^{NS}	Q^{NS}	Q^{NS}	Q^{NS}	Q^{NS}	Q^{NS}	Q^{NS}

[1]Substrates were composed of vermicompost (worm castings) from sheep, horse, or cattle manure and a 70:30 peat moss: perlite mixture (v/v). Electrical conductivity was 0.8 at week 2, 0.2 at week 4, 1.9 at week 6, 1.1 at week 8 and 1.3 at week 10 in Sunshine Mix 1 (SunGro Horticulture, Bellevue, Washington), a commercial substrate used as an additional control.
[2]Means separation using least significant differences at $P \leq 0.05$ within percentage of castings (n=8). Means in rows followed by the same letter do not differ. NS = Nonsignificant. *, ** , and *** = significant at $P \leq 0.05$, 0.01, and 0.001, respectively. L=Linear, Q=Quadratic.

Table 10. Growth index measured at 4 and 10 weeks after planting of 'Miramar' chrysanthemum grown in vermicompost substrates.[1]

Castings	Week 2			Week 8		
	Sheep	Cattle	Horse	Sheep	Cattle	Horse
%	cm^3	cm^3	cm^3	cm^3	cm^3	cm^3
0	7,646a[2]	7,646a	7,646a	10,810a	10,810a	10,810a
25	13,310a	13,137a	12,186a	25,752b	22,330a	21,571a
50	14,044b	11,085a	11,920a	30,439b	17,105a	17,934a
75	9,363b	7,903a	11,775c	15,750b	12,506a	19,259c
100	6,211b	6,090a	7,509b	12,302ab	9,696a	14,416b
Significance	L***	L***	L^{NS}	L*	L***	L^{NS}
	Q***	Q***	Q***	Q***	Q***	Q***

[1]Plants were pinched 2 weeks after planting. Substrates were composed of vermicompost (worm castings) from sheep, horse, or cattle manure and a 70:30 peat moss: perlite mixture (v/v). Growth index = $\pi \cdot \{[(\text{width1} + \text{width2})/2]/2\}^2 \cdot \text{height}$. Growth index measured 2 weeks (10,938 cm) and 8 weeks (18,159 cm) after pinching plants grown in Sunshine Mix 1 (SunGro Horticulture, Bellevue, Washington), a commercial substrate used as an additional control.
[2]Means separation using least significant differences at P≤0.05 within percentage of castings (n=8). Means in rows followed by the same letter do not differ. NS = Nonsignificant. *, ** , and *** = significant at P ≤ 0.05, 0.01, and 0.001, respectively. L=Linear, Q=Quadratic.

sheep casting substrates were not associated with the lowest leachate pH at 10 weeks, but the leachate pH was lower than 6.0 up until week 10. The combination of a low pH and greater nutrient content of sheep castings may have resulted in the greater observed growth. As was also observed by Edwards and Burrows (1988), the substrates with castings had larger plants than the commercial control.

Foliar area and plant dry weight followed a pattern similar to growth index, where foliar area and dry weight increased then decreased as casting concentration increased (Table 11). Greatest foliar area was on plants grown in 50% sheep or horse castings and 25% cattle castings. As with growth index, the greatest foliar area and dry weight were on plants in sheep castings when grown in up to 50% castings, but these measurements were at least as great in horse castings at 75% or 100% castings. The plants in commercial substrate had foliar area and dry weights similar to the plants in sheep castings at 75% and cattle and horse castings at 50%. All plants in castings grew larger, had greater foliar area, and greater dry weight than plants grown in the peat moss: perlite control substrate. Dry matter of mung bean [*Vigna radiata* (L.) R. Wilcz. cv. K851] cultivated in cattle manure compost with earthworms was greater than in compost without earthworms (Sudha et al., 1999). The increased growth was attributed to greater nitrogen and phosphorus uptake when the earthworms were present in the compost.

Flower number peaked on plants grown in 50% sheep or cattle castings and 75% horse castings (Table 11). At 25% and 50% castings, flower number was great-

Table 11. Total foliar area, number of flowers per pot, number of days to flowering, plant dry weight, and depth of substrate (less equals more shrinkage) measured at harvest of 'Miramar' chrysanthemum grown in vermicompost substrates.[1]

Castings	Foliar area			Dry weight			Flower number			Days to flowering			Substrate depth		
	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse	Sheep	Cattle	Horse
%	cm^2	cm^2	cm^2	g	g	g							cm	cm	cm
0	1,870a[2]	1,870a	1,870a	34a	34a	34a	82a	82a	82a	60a	60a	60a	40a	40a	40a
25	4,102b	3,365a	3,354a	74b	67a	67a	188b	169a	1550	52a	54b	53ab	10a	10a	10a
50	4,264b	3,223a	3,385a	81b	66a	65a	218b	173a	165a	52a	54b	56e	10a	10a	10a
75	2,866b	2,301a	3,152e	58b	49a	670	160ab	142a	170b	52a	56b	55b	9a	9a	9a
100	2,425b	2,109a	2,294ab	48b	43a	55e	141b	128a	154b	54a	56b	56b	8a	8a	8a
Significance	L^{NS}	L^{NS}	L^{NS}	L**	L^{NS}	L***	L***	L***	L***	L***	L***	L***	L***	L***	L***
	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***	Q***

[1]Substrates were composed of vermicompost (worm castings) from sheep horse, or cattle manure and a 70:30 peat moss: perlite mixture (v/v). Total foliar area (3,268 ctrv), number of flowers per pot (157), number of days to flowering (55), plant dry weight (63 g), and depth of substrate (10 cm) measured on plants grown in Sunshine Mix 1 (SunGro Horticulture, Bellevue, Washington), a commercial substrate used as an additional control.
[2]Means separation using least significant differences at P≤0.05 within percentage of castings (n=8). Means in rows followed by the same letter do not differ. NS = Nonsignificant. *, ** , and *** = significant at P ≤ 0.05, 0.01, and 0.001, respectively. L=Linear, Q=Quadratic.

est in sheep castings. However, flower number in horse castings at 75% and 100% was as great as or greater than flower number on plants in sheep castings. All plants in castings or the commercial substrate had a greater number of flowers than the peat moss: perlite control.

Growing plants in the peat moss: perlite control delayed flowering by 4 to 7 days (Table 11). Within sheep casting substrates, plants in 100% castings required 2 days longer to flower. Flowering on plants grown in cattle castings occurred 54 days after pinching in 25% and 50% castings and was delayed 2 to 6 days when grown in 0%, 75%, or 100% castings. Plants grown in 25% horse castings flowered 2 to 7 days earlier than in any other horse casting concentration. At all casting concentrations, plants growing in sheep castings flowered earliest compared with those in cattle and horse castings. In the commercial substrate, the plants required 55 days from pinching to flower compared with the earliest flowering in sheep, cattle, and horse at 52, 54, and 53 days, respectively. The earliest flowering occurred in the same substrates that also produced the largest plants and greatest dry weights. Reduced time to flower has also been reported in chrysanthemum, salvia (*Salvia splendens* Sell ex Roem. & Schult.), and petunia (*Petunia xhybrida* Hort. Vilm.-Andr.) grown in vermicompost and was attributed to a proposed presence of hormones in the vermicompost (Edwards and Burrows, 1988).

Substrate depth was measured at harvest to determine the amount of substrate shrinkage due to continued breakdown of the castings that may have occurred during plant growth. Depth remained constant at 10 cm until casting concentration reached 75% (Table 11). At 75% and 100%, substrate depth was reduced to 9 and 8 cm, respectively, for sheep, cattle, and horse castings. Within casting concentration, there was no difference between casting type for substrate depth. This indicated that unless used at concentrations greater than 50%, minimal substrate shrinkage occurred. In addition, it is an indication that the castings, after 1 month of vermicomposting, are relatively stable and exhibit minimal further decay over a 10-week production cycle.

When growing chrysanthemums in soilless substrates, the general pH recommendation is between 5.5 and 6.0 (Ball, 1998). The 50% sheep casting substrate had pH values close to this range during the entire crop cycle. Also, during the first month after transplant, the 50% sheep casting substrate had the greatest EC, and it has been shown that chrysanthemums require high amounts of N and K (Do1e and Wilkins, 1999). Plants grown in mixtures of 25% or 50% sheep castings generally had greater growth index, dry weight, foliar area, number of flowers, and fewer days to flower than plants grown in any other substrate. A constant liquid feed with a 250–400 mg/L balanced fertilizer formula is recommended when growing chrysanthemums in soilless media. High levels of N during the first 7 weeks of the growth cycle are imperative. Deficiencies during this time will reduce the flower quality without chance of recovering (Larson, 1992). No further fertilization is required once the inflorescences reach a diameter of approximately 1.25 cm, as the nutrients required for the flowers during the last 3 weeks of the crop cycle will be translocated from the leaves (Larson, 1992). Even though the crop received a constant liquid feed at 300 mg/L N, the additional nutrients provided from the sheep castings early in production proved beneficial and may have played an important role in the results. Handreck (1986) determined that vermicompost can be used successfully as a potting substrate for ornamental plant species since it provides nutrients required for at least a part of the plant cycle. The length of this time will depend on the plant species and on their nutritional requirement. Handreck (1986) also pointed out that when castings are present in the potting substrate, there was no need for additional microelements and phosphorus, but nitrogen had to be supplied for optimal plant growth.

It cannot be concluded, however, that casting nutrient content alone was the determining factor in better chrysanthemum plant performance. Plants grown in any of the mixtures of castings and peat moss outperformed those grown in 100% castings and the peat moss: perlite control. Casting substrates performed as well as or better than the commercial substrate for all parameters measured.

Growth of chrysanthemum was positively affected by the addition of vermicompost to the substrate. Vermicompost produced from sheep manure outperformed that from cattle or horse manures. Substrates using vermicompost should be formulated with no more than 25–50% castings. Plants grown in 50% sheep or 25% cattle or horse casting substrates were of good, marketable quality, were of greater size, had a greater number of flowers, and flowered earlier than plants grown in either the peat moss: perlite or commercial substrate controls.

Experiment 3

Substrate nutrient analysis showed that castings had a greater nutrient content than the remaining substrates. As anticipated, when castings were mixed with other substrates, nutrient content decreased as a result of dilution. The 4:1 pine bark: sand (v/v) (PBS) treatment had higher P, K, and Zn than the 7:3 peat moss: perlite (v/v) (PP) treatment. PP had the lowest nutrient content of all substrates (Table 12). Similar to our findings, Parkin and Berry (1994) found that earthworm castings were enriched in mineral N, relative to surrounding soil, and the amount of N accumulated in earthworm castings was a reflection of the N content of the organic matter used as a food source by the earthworms. It was previously reported that sheep or cattle castings had greater initial nutrient content than castings from horse manure and substrates with castings (Hidalgo and Harkess, 2002b).

Earthworm castings (C) had the highest pH, followed by 1 PBS: 1 C, 2 PBS: 1 C, and 3 PBS: 1 C. Sunshine Mix 1 and PP had the lowest pH. Research with poinsettia showed that leachate pH of earthworm castings and PP substrates ranged from 4.69 to 8.0, depending on the type and amount of castings (Hidalgo and Harkess, 2002a). In this experiment, PP without castings had a pH between 3.85 and 4.69.

Earthworm castings had a greater amount of soluble salts as indicated by electrolyte conductivity (EC) compared with the control (Sunshine Mix 1), followed by 1 PBS: 1 C, 1 PP: 1 C, and 2 PP: 1 C (Table 13). Substrates with low EC were PBS and PP. These results are associated with higher nutrient levels (Table 12) in the treatments with castings. As previously reported, EC was increased by castings based on the type of castings, and EC decreased with time after transplanting (Hidalgo and Harkess, 2002a).

Earthworm castings, 1 PBS: 1 C, and PP had the greatest percentage pore space followed by 2 PBS: 1 C, 2 PBC: 1 C, and Sunshine Mix 1 (control). PBS, 3 PBS: 1 C, and 1 PP: 1 C had the smallest percentage pore space (Table 13). Percent air space was greatest for PP, followed by earthworm castings as compared with Sunshine Mix 1. Mixtures 3 PBS: 1 C and 2 PBC: 1 C had the smallest percentage air space. These are expected results because perlite is a good substrate to improve aeration of container mixes (Davidson et al., 1994).

Water-holding capacity was greatest for 1 PBS: 1 C as compared with Sunshine Mix 1, followed by earthworm castings. PBS and 1 PP: 1 C had the least water-holding capacity. All treatments containing pine bark: sand had the highest values for bulk density, followed by 1 PP: 1 C, 2 PP: 1 C, and earthworm castings. Sunshine Mix 1 and 7:3 peat moss: perlite had the lowest bulk density. Davidson et al. (1994) stated that peat moss is difficult to wet, but when it is wet, it possesses good water-holding capacity and good aeration. In this study, treatments containing peat moss showed reduced water-holding capacity, possibly as a result of a short wetting period of 30 minutes. Syers and Springett (1983) found that earthworm castings generally have higher water-holding capacity compared with soil without castings.

Castings alone and 1 PP: 1 C had the greatest growth index (GI) but did not differ from 2 PP: 1 C or 1 PBS: 1 C (Table 14). All treatments except PP and 3 PBS: 1 C resulted in a greater GI compared with Sunshine Mix 1 (control). PBS resulted in the lowest growth index. Greater amount of nutrients, higher pH, and increased water-holding capacity found in castings may have resulted in a greater plant growth index. In plant growth trials with vegetables, fruits, and ornamental plants, vermicompost outperformed both

Table 12. Extractable nutrient levels of the treatment substrates used to grow marigolds.

Substrates	Extractable nutrient levels					
	N	P	K	Ca	Mg	Zn
	mg/kg	*mg/kg*	*mg/kg*	*mg/kg*	*mg/kg*	*mg/kg*
Sunshine	4.0g[1]	23.0d	89.5i	818.5h	252.5f	13.8b
Castings	65.0a	165.5b	567.5a	2,431.5a	577.5a	17.9a
4 Pine bark : 1 sand (PBS)	0.5h	15.0e	91.5h	789.5i	79.5i	2.7h
7 Peat moss : 3 perlite (PP)	0.5h	2.5f	10.5j	193.0j	55.5j	1.1i
1 PP : 1 C	12.5d	166.5a	445.5c	1,333.5e	349.0c	9.2d
2 PP : 1 C	9.0e	161.5c	331.5e	1,246.0d	247.5g	8.1e
3 PP : 1 C	17.5b	161.5c	281.0g	1,173.0e	222.5h	6.6fg
1 PBS : 1 C	15.0c	161.0c	531.0b	1,820.5b	390.0b	11.6c
2 PBS : 1 C	6.5f	161.0c	367.5d	1,061.0f	294.0d	7.0f
3 PBS : 1C	4.5g	161.0c	300.5f	966.0g	261.5e	5.9g

[1]Means in columns separated by Duncan's multiple range test 5% significance level. Means in columns followed by the same letter do not differ.

Table 13. Percentage pore space, air space, water-holding capacity, bulk density, pH, and EC of the different substrates used to grow marigold plants.

Substrates	Pore space	Air	Water-holding capacity	Bulk density	pH	EC
	%	*%*	*%*	*g/cm*		*mmhos/cm*
Sunshine Mix 1	66b[1]	13c	53bcd	0.10e	5.67f	0.42de
Castings	82a	22b	60b	0.22c	7.59a	0.90a
4 pine bark : 1 sand (PBS)	45c	6de	39e	0.47a	6.59c	0.10bg
7 peat moss : 3 perlite (PP)	80a	36a	44de	0.13de	5.80f	0.15g
1 PP : 1C	52c	13c	39e	0.26b	6.37d	0.50bc
2 PP : 1C	62b	8c	54bc	0.24bc	6.17d	0.50bc
3 PP : 1C	52b	11cd	41e	0.16d	6.11e	0.38ef
1 PBS : 1 C	82a	10cd	72a	0.44a	6.80b	0.55b
2 PBS : 1 C	62b	5de	56bc	0.46a	6.63c	0.39ef
3 PBS : 1 C	50c	3e	46cde	0.48a	6.56c	0.34f

[1]Means in column separated by Duncan's multiple range test 5% significance level. Means in columns followed by the same letter do not differ.

traditional compost and commercial plant growth substrates in almost every experiment. The author stated that this may be explained, partially by circumstantial evidence, that vermicomposts have better structure and may contain plant growth hormones, enhanced levels of soil enzymes, and high microbial populations (Edwards, 1995).

Castings alone resulted in greater marigold stem diameter each week after transplanting as compared with the remaining substrates (Table 14). Greater nutrient content of the castings when compared with the rest of substrates may explain the increase in stem diameter. PBS resulted in smallest stem diameter. Earthworm castings and Sunshine Mix 1 resulted in greater number of roots and were equally effective compared with the remaining treatments (Table 14). The number of roots in Sunshine Mix 1 did not differ from pine bark castings mixtures (PBS: C).

Earthworm castings increased plant dry weight, followed by 1 PP: 1 C, 1 PBS: 1 C, and 2 PP: 1 C, when compared with Sunshine Mix 1 (control). PP and PBS resulted in least dry weight of marigolds. The remaining treatments showed intermediate values not different from the control (Table 14).

Earthworm castings increased the number of flowers compared with the remaining substrates (Table 14). When substrates were mixed with castings at 1:1, 2:1, or 3:1 (v/v), performance was related to the amount of castings in the mixtures; the greater the amount of castings, the greater the growth response. This improvement could have been associated with increasing amount of nutrients obtained when castings were increased in the mixture, in addition to the physical and chemical properties of castings. Castings had a greater nutrient content, particularly nitrogen, than the other substrates. PP had the lowest nutrient content of all substrates. In addition, castings had the highest pH and EC and contributed to greater air space and water-holding capacity, which contributed to improved plant growth. Castings were found to be a suitable substrate amendment for growing potted marigolds.

Table 14. Growth index (GI), root growth, plant dry weight, stem diameter, number of flowers per plant, and number of flowers opened per plant of marigold as influenced by substrates 9 weeks after transplanting.

Substrates	Growth index	Root growth	Dry weight	Stem diameter	Flowers	Open flowers
	cm^3	*1–5[1]*	*g*	*mm*	*no.*	*no.*
Sunshine Mix 1	2,164.7d[2]	4.0ab	4cd	5ef	1cde	0.0c
Castings	3,449.2a	4.8a	10a	7a	3a	0.8a
4 pine bark : 1 sand (PBS)	1,461.7e	2.6cd	2e	4g	0e	0.0c
7 peat moss : 3 perlite (PP)	2,253.1d	2.6cd	3de	4de	1de	0.0c
1 PP : 1 C	3,450.1a	2.8cd	6b	6b	3ab	0.6ab
2 PP : 1 C	3,078.1ab	2.2d	5c	6bcd	2bcd	0.2bc
3 PP : 1 C	2,884.9bc	2.0d	4cd	5de	2abc	0.0c
1 PBS : 1 C	3,031.0ab	3.8b	6b	6bcd	2bcd	0.4abc
2 PBS : 1 C	2,721.8bc	3.6c	5bc	5cde	1cde	0.0c
3 PBS : 1 C	2,418.1cd	3.6bc	4cd	5de	2bcd	0.0c

[1]Visual scales from 1–5 in which 5 = excellent number of roots and I = poor number of roots.
[2]Means in column separated by Duncan's multiple range test 5% significance level. Means in columns followed by the same letter do not differ.

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